Creating a Fuels Baseline and Establishing Fire Frequency Relationships to Develop a Landscape Management Strategy at the Savannah River Site

Bernard R. Parresol[1], Dan Shea[2], and Roger Ottmar[3]

Abstract—*The Savannah River Site is a Department of Energy Nuclear Defense Facility and a National Environmental Research Park located in the upper coastal plain of South Carolina. Prescribed burning is conducted on 15,000 to 20,000 ac annually. We modified standard forest inventory methods to incorporate a complete assessment of fuel components on 622 plots, assessing coarse woody debris, ladder fuels, and the litter and duff layers. Because of deficiencies in south-wide data on litter-duff bulk densities, which are the fuels most often consumed in prescribed fires, we developed new bulk density relationships. Total surface fuel loading across the landscape ranged from 0.8 to 48.7 tons/ac. The variables basal area, stand age, and site index were important in accounting for variability in ladder fuel, coarse woody debris, and litter-duff for pine types. For a given pine stand condition, litter-duff loading decreased in direct proportion to the number of burns in the preceding thirty years. Ladder fuels for loblolly and longleaf increased in direct proportion to the years since the last prescribed burn. The pattern of fuel loading on the SRS reflects stand dynamics, stand management and fire management. It is suggested that the Forest Inventory and Analysis Program can easily modify sampling protocols to incorporate collection of fuels data.*

Introduction

The Savannah River Site (SRS) is a 198,344 ac land base controlled by the Department of Energy. The SRS is a Nuclear Defense Facility and a National Environmental Research Park. The SRS is located on the Upper Coastal Plain and Sandhills physiographic provinces, south of the city of Aiken, South Carolina (figure 1). Created in 1951, the SRS today contains approximately 182,420 ac of forested landscape divided into 6,009 stands across six expansive management areas.

When the SRS was established, approximately 80,000 acres were in old-fields and the balance consisted of cut over forest land with low stocking (Kilgo and Blake 2005). The planting of the old fields and cutover forests with (non-native) slash pine (*Pinus echinata*), loblolly pine (*P. taeda*) and longleaf pine (*P. palustris*) created a large block in a narrow age class and a dynamic fuel loading problem. Approximately 14 wildfires, primarily surface fires, occur each year. An effective prescribed burning program was not initiated until the mid 1970's. Today prescribed burning is conducted on 15,000 to 20,000 acres annually to reduce fire hazards and to enhance ecological communities associated with longleaf fire savannas. The SRS has also utilized herbicides to reduce mid-story vegetation, primarily for management of the endangered

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Biometrician, USDA Forest Service, Southern Research Station, Asheville, NC. bparresol@fs.fed.us.

[2] Fire Planner, USDA Forest Service, Savannah River, New Ellenton, SC.

[3] Research Forester, USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

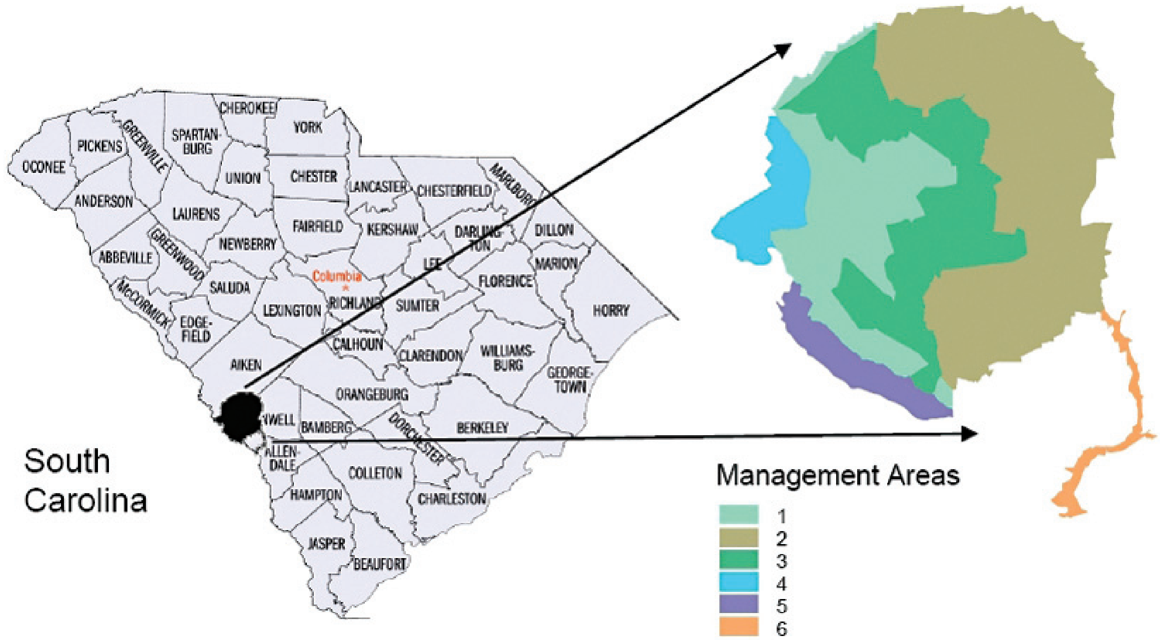


Figure 1—Location of the Savannah River Site in Aiken, Barnwell, and Allendale counties, South Carolina. The six expansive management areas are shown.

red cockaded woodpecker (*Picoides borealis*), and mechanical shredding. More recently sub-merchantable woody fuels are being considered as a fuel supply for a bioenergy fired power facility on-site. However, prescribed burning is the most cost effective technique on per acre basis. Because of smoke management constraints, which limits prescribed burning and the high costs of alternative fuel treatments, there was an identified need to optimize fuels management, including the types of stands to be treated, their location on the landscape, and the frequency of treatment.

The Need for Fuels Inventory

There are currently no periodic regional or national fuels inventories being conducted. The lack of periodic field inventories makes it impossible to gauge the effectiveness of national, regional or local fuels and fire management policies and strategies. Remote sensing methods are largely unable to accurately estimate surface fuels (Keane and others 2000) that are the main contributors to fire behavior in the South. Because of the identified need to optimize fuels management at the Savannah River Site, the periodic inventories conducted on-site were modified to include measurement of forest floor fuel variables. Small mid-story trees that contribute to ladder fuel were being captured by the existing design. Our objective was to establish a fuel loading baseline as a function of stand variables as a reference for Site management, to allocate fuel treatment strategies, and to estimate the prescribed burning frequency needed to achieve wildfire behavior objectives.

Inventory Design and Fuels Sampling

A systematic layout of sample points was installed using an approximate 1000- by 1000-meter grid over the entire SRS land base, except for the narrow corridor along the Lower Three Runs Creek that extends from the southeast boundary to the Savannah River. This resulted in approximately one sample plot per every 250 acres of the SRS, or 773 plot locations. This plot density is high from the traditional inventory perspective. Of the 773 plots, only 657 fell on forested areas. An additional data source of 62 plots that fall on the SRS from the Forest Inventory and Analysis (FIA) regional inventory (conducted by the USDA Forest Service) are included in the plot database. Combining the 62 regional inventory plots that fall on the SRS with the 657 new SRS plots produces a potential sample of 719 points (figure 2).

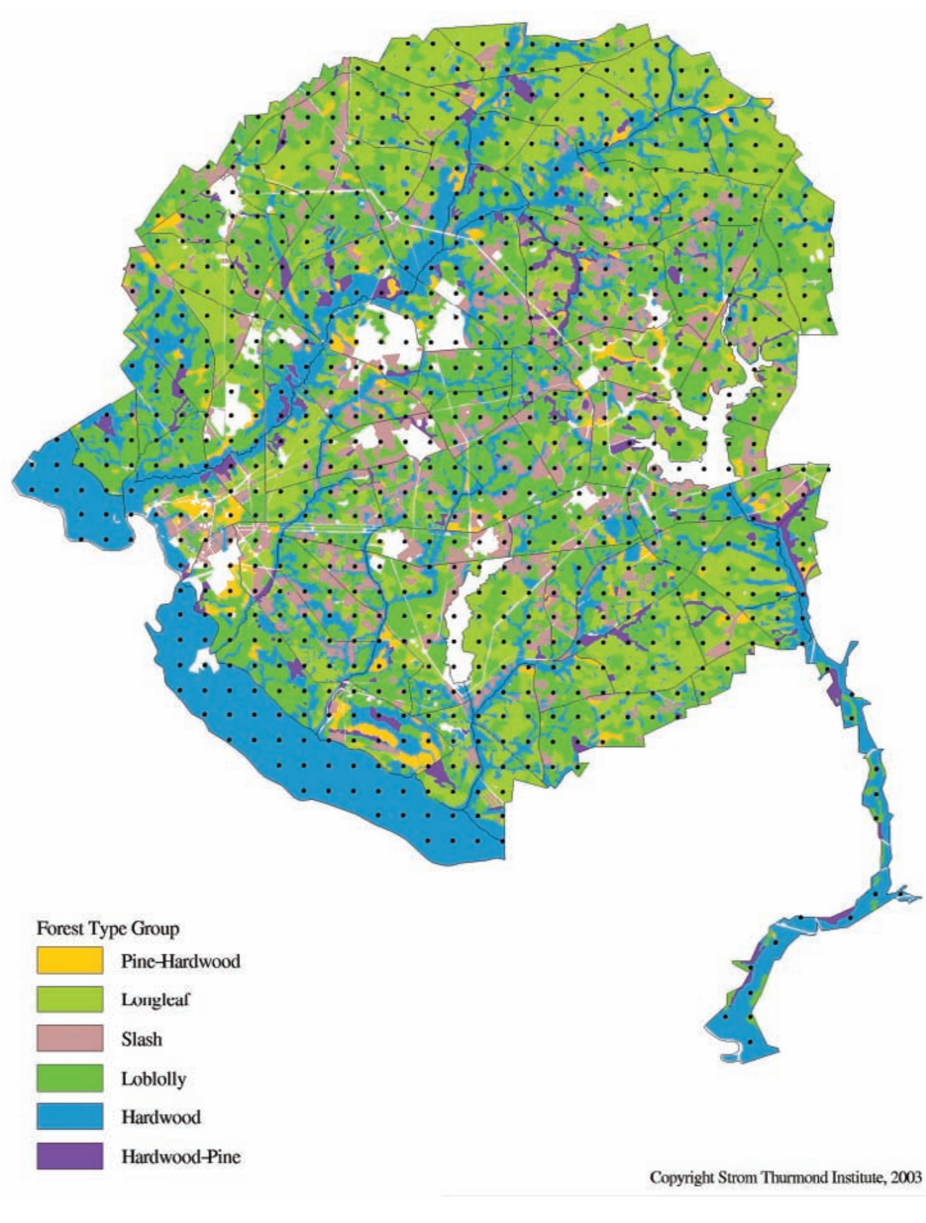


Figure 2—Systematic layout of inventory plots on the Savannah River Site and spatial distribution of the broad forest type groups.

The plot design used is a standard FIA design commonly used in the southeastern U.S. It consists of a cluster of five subplots, 70 feet between points, which are normally laid out in the scheme shown in figure 3. Two nested plot-types are established at each of these five subplot center points. One of these plot-types is a variable-radius plot using a 37.5-factor angle prism for sampling trees that are 5-inches or larger in diameter at breast height (dbh). Nested at the same point is a circular fixed-radius 1/300th-acre plot for sampling trees from 1- to 5-inches in diameter. All sampled trees from the five subplots are combined, meaning that the operative prism factor for the sample location (that is, the 5 subplots) is 7.5, and the cumulative area of the fixed-radius plots is 1/60th of an acre. The pattern shown in figure 3 is the standard subplot layout, but the arrangement was altered when necessary to insure that all subplots fall within the same stand or forest condition found at subplot 1. It was necessary to alter this arrangement in about a third of the plots on the SRS. Subplot 1 is never moved from the initially selected point location. Rotation only occurs on subplot 2 to 5, for the purpose of matching their forest condition with that of subplot 1.

In-between the five subplots are four planar transects used for measuring coarse woody debris (CWD) forest floor fuel (figure 4). These measurements are on dead woody material that has separated from the plant (trees and shrubs) that produced it, or from main stems of dead trees that have fallen down. The method for measuring CWD uses a vertical-plane-intersect plot that either counts by size class for smaller material or measures the individual diameters for diameters greater than 3 inches the pieces of CWD material that break the plot plane (Brown 1974). As shown in figure 4, counts were made along a 10-foot section of the transect line of dead downed material with diameters of 0-0.25 inches (1-hour fuels). Counts of pieces with diameters in the 0.25-1.0 inch range (10-hour fuels) were made at the same time along the same 10-foot section of the transect line. Counts were made of pieces with diameters of 1.0-3.0 inches (100-hour fuels) along a 20-foot transect. Dead downed material larger than 3 inches diameter encountered along the full 70-foot transect had their individual diameters at the point of intersection measured, and their condition was classed as either solid or

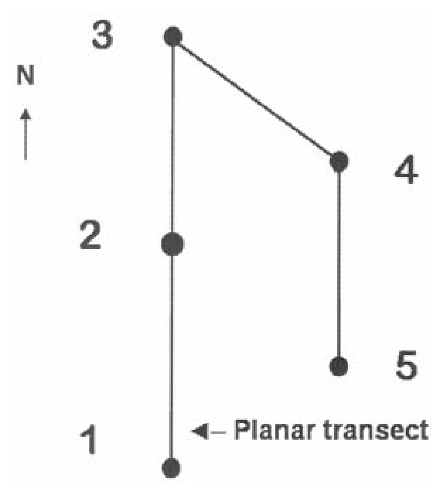


Figure 3—Plot design used at the Savannah River Site showing standard orientation of the 5 subplots and the 4 planar transects.

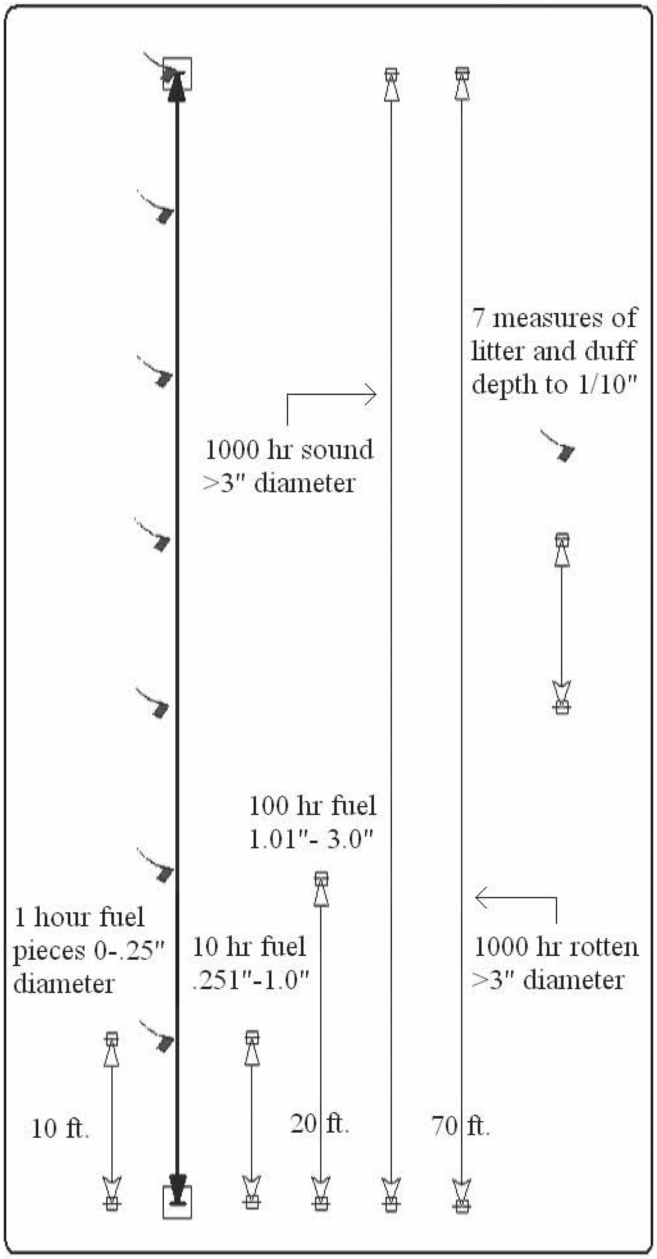


Figure 4—Design of the Brown's planar transect for measuring coarse woody debris and litter and duff depths.

rotten. Seven measurements of litter and duff depth to the nearest 1/10th inch were taken at ten-foot intervals along each of the 70-foot transect lines. An inventory of 622 plots (from the 719 possible) was started in March 1999 and completed in January 2002.

Bulk Density Study

Because of deficiencies in south-wide data on litter-duff bulk densities, which are the fuels most often consumed in prescribed fires, a study was undertaken to develop new bulk density relationships. There have been several studies in the past to collect bulk density values for forested areas of the south. However, these studies were very limited in scope (Scholl and Waldrop 1999) or were completed at locations other than at the Savannah River Site (Ottmar and Vihnanek 2000; Ottmar and others 2003; McNab and others 1978). The primary objective for the study was to determine bulk density conversion factors to convert litter and duff depth values in inches to forest floor fuel values in tons per acre. This was done for combinations of four common forest types (loblolly/slash pine, longleaf pine, pine and hardwood mix, upland hardwood), 3 age classes (5-20, 20-40, 40+ years old) and 3 categories of burning history (0-3, 3-10, 10+ years since last burn).

Bulk density sampling points were randomly selected from the 622 inventory plots of the 1999-2002 inventory period. Random points were selected from groups of plots based on the aforementioned stand type, stand age, and rough age. Within each sample site, subplot 1 was designated as the plot center. The lower left bulk density sample square point was established 33 feet from the plot center at each of the four cardinal directions (figure 5). A 12-inch beveled steel square was positioned on top of the forest floor. Twelve markers (6 inch gutter nails) were then placed in a grid pattern evenly within the square (figure 5). The nails were tapped downwards until the top of the

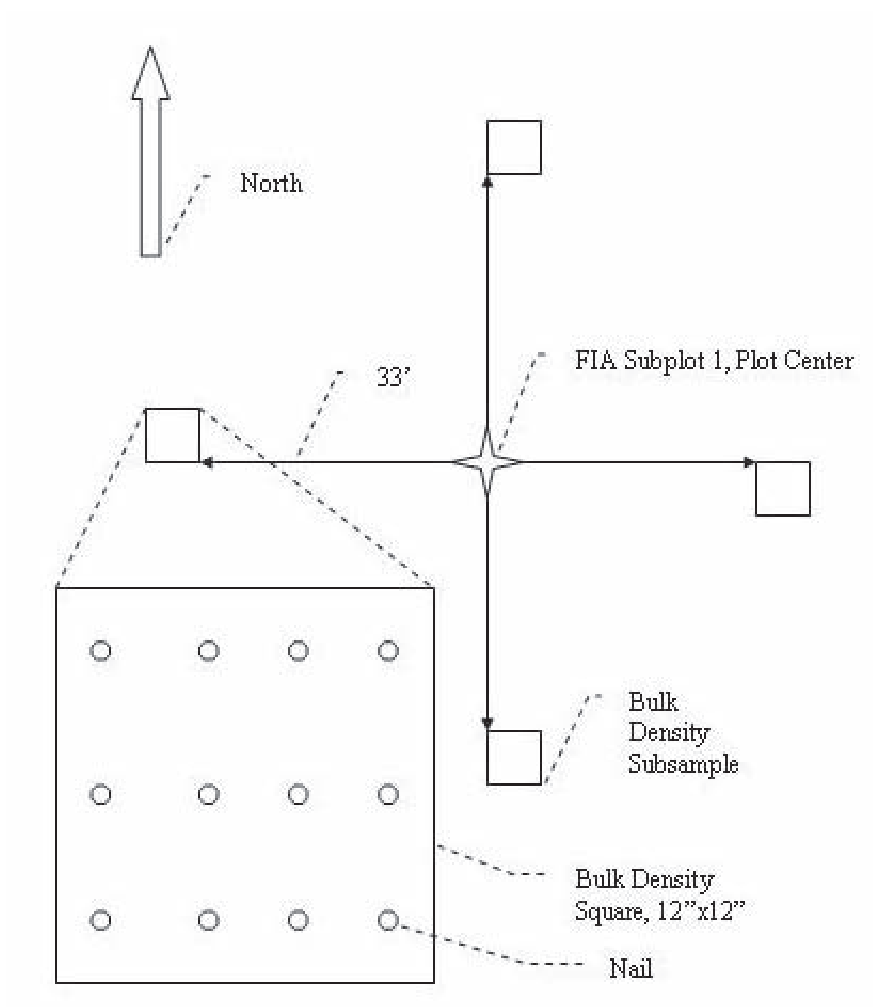


Figure 5—Sample plot layout for the Savannah River bulk density project.

nail was flush with the top of the litter layer. Litter was then carefully removed from the square and placed within a labeled bag. The distance between the top of each marker and the top of the duff layer was measured and recorded. The average of these twelve depth measurements represents the litter depth for the sample. After measurements were recorded, the markers (nails) were again tapped down so that the tops were all flush with the top of the duff layer. The duff layer was then carefully removed, placed in a labeled bag, and the distance between the top of the marker and the substrate was measured, the average of these twelve measurements represents the duff depth for the sample. All litter and duff samples were taken to the lab and oven dried for 48 hours. Litter samples were dried at 70 degrees Celsius and duff samples at 100 degrees Celsius. For further details and results see Maier and others (2004) and Parresol (2005).

Fuels Computation

Computation of biomass for each fuel component was done in a different fashion. For ladder fuels (i.e., non-merchantable arborescents of *Pinus*, *Juniperous*, *Taxodium* < 5" dbh and hardwoods < 6" dbh) biomass equations were utilized (Brown and others 1997). The coarse woody debris subcomponents were converted to biomass using formulas from Brown (1974). These formulas to compute tons/ac are:

$$\text{0- to 3-inch material:} \quad = \frac{11.64 \times n \times d^2 \times s \times a \times c}{L}$$

$$\text{3+-inch material} \quad : \quad = \frac{11.64 \times \Sigma d^2 \times s \times a \times c}{L}$$

where n is number of particles counted in each size class along a line transect, d is average particle diameter for the 0- to 3-inch size classes and d is measured diameter for pieces 3"+, s is wood specific gravity, a is the nonhorizontal angle correction factor (the correction factor adjusts weight estimates for the fact that all particles do not lie horizontally as assumed in the planar intersect theory), c is the slope correction factor for converting weight/ac on a slope basis to a horizontal basis, and L is the transect length in ft. The percent slope was measured at each inventory plot and the slope correction factor was calculated as $c = \sqrt{1 + (\text{percent slope}/100)^2}$. The following values for average d^2, s, a, and L were used:

Size class	d ^{2}	s	a	L
0 – 0.25"	0.0151	0.7	1.13	40
0.25" - 1"	0.289	0.7	1.13	40
1" - 3"	2.76	0.58	1	80
3"+ sound	—	0.58	1	280
3"+ rotten	—	0.3	1	280

For the litter and duff calculations subplots were averaged for a combined average litter-duff depth for each inventory plot. Bulk density conversion factors determined from the bulk density study were applied to the averaged depth value for each plot to compute litter-duff tons/ac. See Parresol (2004) for a detailed description of the fuel loading computations.

Broad Species Groups

The SRS contains 25 naturally occurring mixtures of species or stand types (see Hansen and others 1992). For analysis purposes we grouped the 25 stand types into seven broad species composition groupings defined on the basis of the forest types as given in table 1. For each of the 622 inventory plots, a forest type was assigned based on each individual plot species make-up, by applying the following Forest Service definitions:

1) to be assigned to one of the three yellow pine forest types, 70% or more of the total basal area of the stand must be in yellow pine, and then it is assigned to a particular yellow pine species based on the species (loblolly, longleaf, or slash pine) with the largest basal area component,
2) to be assigned to the pine-hardwood type the plot must have ≥50% and <70% of the total basal area in yellow pines species,
3) to be assigned to the hardwood-pine type the plot must have >30% and <50% of the total basal area in yellow pines species, and
4) to be assigned to the hardwood type, < 30% of the total stand basal area must be in yellow pine species.
5) to be assigned to the cypress/tupelo type, ≥50% of the total stand basal area must be in baldcypress (*Taxodium distichum*)and/or tupelo (*Nyssa* sp.).

The inventory plots were grouped into the broad categories previously identified in table 1 based on their observed species make up derived from applying the above definitions. Examples of forest types are shown in figure 6. This resulted in the distribution of inventory plots into the forest type groups as given in table 1. The cypress/tupelo stands are set-aside areas and are not considered further.

Analysis

For analysis purposes we combined litter and duff, and added all components for total fuel. For each broad species group we ran a factorial analysis of variance (ANOVA) on 5 factors, site index class (SIC) where site index (SI) is stand height in ft at 50 years, basal area class (BAC) where basal area (BA) is measured in ft^2/ac, age class (AC) where age is years, number of burns class (NBC) where number of burns (NB) is a count of prescribed burns in a stand,

Table 1—The forest stands on the Savannah River Site categorized into seven broad species composition groups linked with the relevant Forest Service forest types.

Group	Group Name	Forest Types Included	# Stands	Acres	Percent	# Plots
1	Loblolly pine	25, 31, 32	1897	62,602	34.32	277
2	Longleaf pine	21, 26, 34	1151	43,294	23.73	129
3	Slash pine	22	618	17,716	9.71	58
4	Pine-Hardwood mix	12, 13, 14, 35	272	5,340	2.93	23
5	Hardwood-Pine mix	44, 46, 47, 48, 49	214	5,355	2.94	27
6	Hardwoods	51, 52, 53, 54, 56, 57, 58, 61, 62, 63, 64, 68, 72, 82, 98	1739	41,436	22.71	103
7	Cypress/Tupelo	67	118	6,677	3.66	5
			6,009	182,420	100.00	622

a

b

Figure 6—Examples of forest types occuring on the Savannah River Site: a) longleaf pine plantation, b) natural stand of mixed hardwoods.

and number of years since last burn class (YSBC) where years since last burn (YSB) is time in years or fraction thereof from the most recent prescribed burn. The definition of SIC is: if SI < 70 ft then SIC=1, if 70 < SI ≤ 80 then SIC=2, if SI > 80 then SIC=3. The definition of BAC is: if plot BA ≤ 82.5 ft^2/ac then BAC=1, if 82.5 < BA ≤ 111.5 then BAC=2, if plot BA > 111.5 then BAC=3. The definition of age class (AC) is: if age ≤ 4 then AC='A, if 5 ≤ age ≤ 17 then AC='B', if 18 ≤ age ≤ 35 then AC='C', if age ≥ 36 then AC='D'. Number of burns class is 0, 1, 2, 3+. Years since last burn class is defined as: if YSB ≤ 3 then YSBC=1, if 4 ≤ YSB ≤ 9 then YSBC=2, if YSB ≥ 10 then YSBC=3. We also examined the impact of the 5 analysis variables through running a series of stepwise linear least squares regressions by broad species group. To examine trends in more detail, that is, to investigate the role of stand dynamics and effect of prescribed burning, we present a series of regression response surfaces using longleaf pine to illustrate.

Results

Bulk Density Study

Bulk density conversion factors are given in table 2. Average litter bulk densities ranged from 1.5 tons/ac/in for mixed pine and hardwood stands between 5-20 years old without fire for over 10 years to 2.4 tons/ac/in for loblolly and slash pine sites between 5 and 20 years in age and more than 3 years since fire. Average duff bulk densities ranged from 2.6 tons/ac/in on mixed upland hardwood stands between 5 and 20 years in age with greater than 10 years since fire to 9.0 tons/ac/in for loblolly and slash pine greater than 40 years in age and 3 to 10 years since fire.

Fuel Loading

Fuel loading weight in tons across the entire SRS are given in table 3 by broad forest type. Fuel weights are displayed by the fuel categories conifer fuel trees, hardwood fuel trees, CWD, and litter-duff. Table 4 has the same structure as table 3 except average fuel weight in tons per acre is given in

Table 2—Litter and duff bulk densities (tons/acre/inch) for forest types by age class (years) and rough age (years).

		Forest Type							
		Lob/Slash		LL		PH Mix		UH Mix	
Age Class	Rough Age	Litter	Duff	Litter	Duff	Litter	Duff	Litter	Duff
	0-3	—	—	1.8	3.8	—	—	—	—
5-20	3-10	2.0	4.4	1.6	4.5	—	—	—	—
	10+	1.9	4.8	1.8	4.1	1.5	3.9	1.8	2.6
	0-3	2.4	6.0	2.6	8.2	2.8	6.7	—	—
21-40	3-10	2.4	6.4	2.9	6.3	1.6	5.3	1.9	5.1
	10+	1.9	5.9	2.7	8.6	1.7	4.0	2.1	5.7
	0-3	1.9	6.4	2.2	8.2	2.1	8.8	2.2	6.6
40+	3-10	2.3	9.0	2.1	7.0	2.2	7.0	1.9	6.2
	10+	2.3	7.2	2.5	8.2	2.0	5.3	2.0	7.1

Note: Lob is loblolly pine, LL is longleaf pine, PH Mix is mixed species pine-hardwood stand, UH Mix is mixed species upland hardwood stand, and rough age is number of years since last burn.

Table 3—Fuel loadings in tons from the 1999-2002 Savannah River Site inventory of 622 plots.

	Forest Type						
Fuel Type	Loblolly	Longleaf	Slash	Pine-Hdwd	Hdwd-Pine	Hdwd	All Types
	Tons						
Conifer trees	160,949.2	86,854.5	36,242.4	1,821.3	15.5	4,120.8	290,003.7
Hdwd trees	232,256.3	80,439.4	50,093.5	34,619.4	40,828.3	314,243.7	752,480.6
CWD	233,994.5	150,301.2	79,926.2	28,655.6	22,147.1	149,620.5	664,645.1
Litter-duff	93,503.5	58,705.5	31,645.3	6,476.7	5,402.6	36,668.3	232,401.9
						Overall Total:	1,939,531.3

Note: Hdwd is hardwood, CWD is coarse woody debris.

Table 4—Average fuel loadings in tons/ac from the 1999-2002 Savannah River Site inventory of 622 plots.

	Forest Type						
Fuel Type	Loblolly	Longleaf	Slash	Pine-Hdwd	Hdwd-Pine	Hdwd	All Types
	Tons						
Conifer trees	2.571	2.006	2.046	0.357	0.003	0.107	1.684
Hdwd trees	3.710	1.858	2.828	6.784	8.109	8.167	4.369
CWD	3.738	3.472	4.512	5.615	4.399	3.888	3.859
Litter-duff	1.494	1.356	1.786	1.269	1.073	0.953	1.349
						Average:	11.261

Note: Hdwd is hardwood, CWD is coarse woody debris.

the table cells. The overall fuel tonnage for the 172,228 acres covered in the fuels inventory is 1,939,531 tons giving an average per acre value of 11.3 tons. This average breaks down as follows: 1.7 tons/ac in conifer fuel trees, 4.4 tons/ac in hardwood fuel trees, 3.9 tons/ac in CWD, and 1.3 tons/ac in litter/duff.

Analysis of Variance

The results of the ANOVAs are outlined in table 5. All factors shown in table 5 were significant at the $\alpha = 0.05$ level. As can be seen in this table, loblolly and longleaf pine had a number of significant factors. Our explanation for the nonsignificance with slash involves land-use history. Slash is an off-site species, planted primarily in old-fields with a small range in age, BA and SI, so there is very little variability among the stands. However, using stand variables as a continuum in the linear regressions shows significant effects despite the small range in values, as seen in the next section. The ANOVAs indicate the complex interplay of factors involved in trying to understand fuel loadings.

Table 5—Significant (P<0.05) class variables and interactions by forest type.

Forest Type	Ladder Fuel	CWD	Litter-Duff	Total Fuel
Loblolly	BAC, AC, SIC×YSBC, NBC×YSBC	AC	BAC, AC, SIC×BAC	None
Longleaf	SIC, BAC, AC BAC×AC SIC×YSBC	BAC, SIC×AC, SIC×NBC	None BAC×AC	SIC, BAC, AC
Slash	None	None	None	None
Pine-Hdwd	BAC, NBC	None	None	None

Note: Hdwd is hardwood, CWD is coarse woody debris, BAC is basal area class, AC is age class, SIC is site index class, YSBC is years since last prescribed burn class, and NBC is number of prescribed burns class. Please see text for definitions of classes.

Stepwise Linear Least Squares Regressions

More informative than the ANOVAs are the inferences from the linear regressions. The significant variables from the linear regressions are given in the table 6. Basal area and age are important explanatory variables for estimating fuel loading in loblolly pine stands. In terms of prescribed burning, loblolly ladder fuel and CWD were affected by years since last burn, while the litter-duff layers were affected by number of burns. Site index, basal area and stand age were all critical in determining longleaf pine stand fuel loadings. For longleaf, ladder fuel was affected by years since last burn, but burning in this linear context did not seem to affect the CWD or litter-duff layers. Because of the importance of longleaf pine management at the SRS, response was examined more closely using nonlinear models and log-transformed models. Those results are given in the next section. For slash pine, years since the last burn was correlated with CWD and number of burns affected the litter-duff layers. Finally for the pine-hardwood mix, the CWD was correlated with years since last burn. While stand characteristics play a major role in overall fuel loads, the prescribed burning program is having significant impacts on reducing fuel components.

Response Surfaces

To more fully understand the effects of stand variables and the impact of the prescribed burning program, a series of best-fit empirical regression relationships for longleaf pine were developed to generate response surfaces. Equations for ladder fuel (equation 1), litter-duff (equation 2), 1 hour fuel

Table 6—Signicant variables (P<0.05) from the stepwise linear least squares regressions.

Forest Type	Ladder Fuel	CWD	Litter-Duff	Total Fuel
Loblolly	BA, A, YSB	A, YSB	BA, A, NB	BA
Longleaf	SI, BA, A, YSB	SI, BA, A	BA	SI, BA, A, YSB
Slash	SI, BA	YSB	BA, NB	BA
Pine-Hdwd	SI, BA	SI,YSB	None	BA

Note: Hdwd is hardwood, BA is basal area in ft^2/ac, A is age in yeasrs, SI is site index in ft base age 50, YSB is years since last prescribed burn, and NB is number of prescribed burns.

(equation 3), 10 hour fuel (equation 4), and the 100+ hour fuel (equation 5) are given below.

$$\widehat{ladder\ fuel} = 50.217\,exp\left(-0.036SI + 0.014BA - 0.033Age + 0.00102YSB^2\right)$$
$$R^2 = 0.51, RMSE = 3.50 \tag{1}$$

$$\widehat{litter\text{-}duff} = 0.598 + 0.0127BA - 0.374 / YSB$$
$$R^2 = 0.45, RMSE = 0.57 \tag{2}$$

$$\widehat{\ln 1\,hour\ \ fuel} = 4.082 - 0.206\ln Age - 1.659\ln SI - 0.257\ln NB$$
$$R^2 = 0.084, RMSE = 0.966 \tag{3}$$

$$\widehat{\ln 10\,hour\ \ fuel} = -1.429 + 0.272\ln Age + 0.075\ln YSB$$
$$R^2 = 0.11, RMSE = 0.836 \tag{4}$$

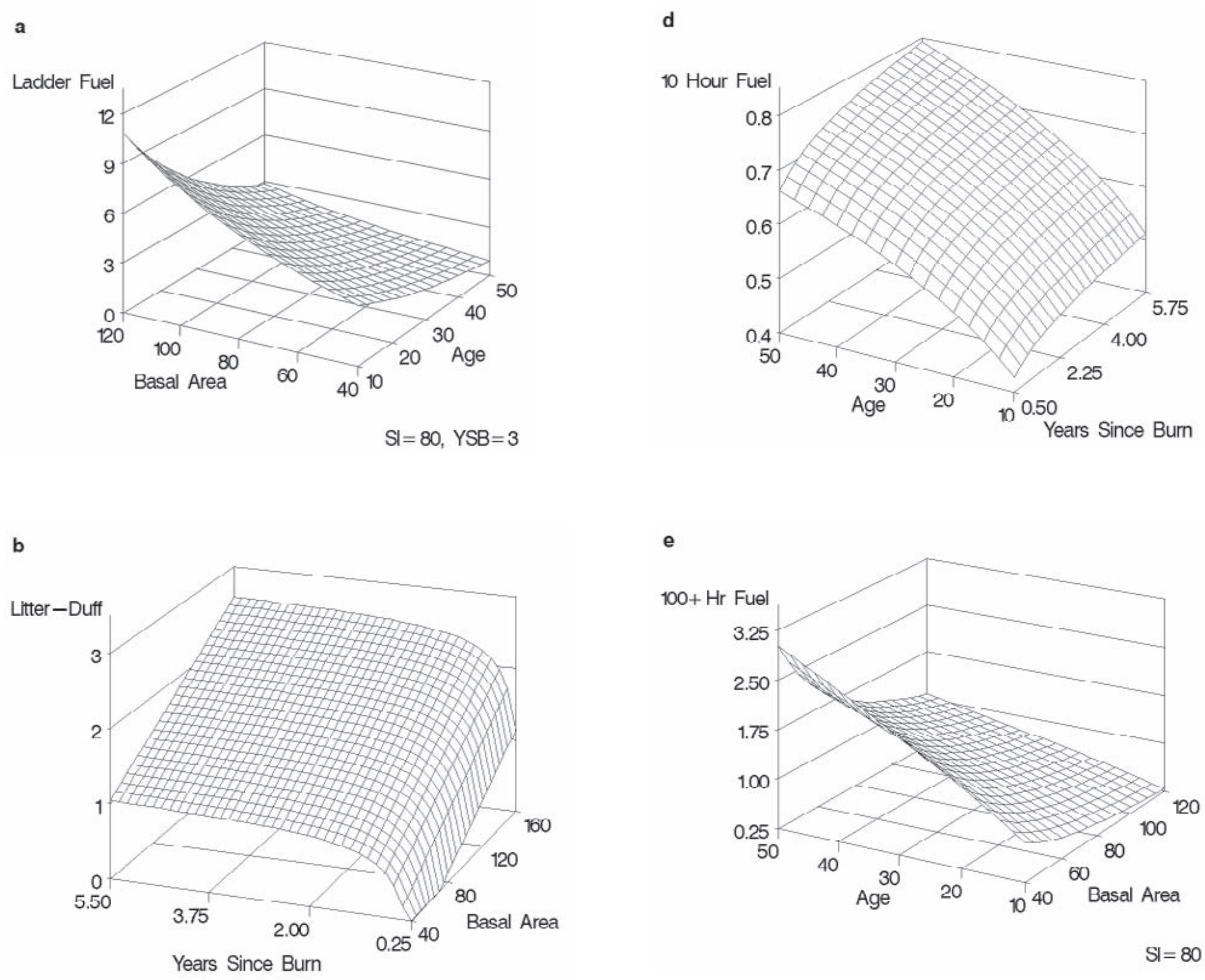
$$\widehat{\ln 100 + hour\ \ fuel} = -6.071 - 0.939\ln BA + 0.803\ln Age + 1.710\ln SI$$
$$R^2 = 0.15, RMSE = 1.373 \tag{5}$$

Figure 7 shows the response surfaces generated from these equations. Figure 7a shows that ladder fuels are generally determined by BA and age, decreasing as BA decreases and age increases. Equation 1 shows that YSB has a small but statistically significant effect in reducing ladder fuels. Figure 7b shows the dramatic effect both YSB and BA has on determining litter and duff fuel loading. It is clear that litter-duff loadings recover quickly, in as little as two to three years after a burn. Figure 7c shows that the 1 hour fuel is reduced through repeated burning and that SI also plays a role. Figure 7d indicates that recency of burn has some impact on the 10 hour fuel but that age is the main factor determining fuel load. Finally, equation 5 and figure 7e reveal that burning has no detectable effect on the 100+ hour fuel, but rather the interplay of age, BA and SI.

Discussion

Field fuel inventories are generally not available at local, regional or national scales. At the SRS managers identified the need for such information to help guide decision making concerning fuels management. We easily modified standard forest inventory methods to incorporate a complete assessment of fuel components on the SRS. The FIA program of the USDA Forest Service inventories the entire U.S. forest resources periodically and is moving towards an annual multi-resource inventory system. A suite of habitat and environmental variables are collected along with the more traditional tree measurements. From our experience with this project, we were able to easily incorporate fuel variables into our inventory design and we strongly believe and recommend that the FIA program nationally can achieve the same objective. The average number of man days per plot was equal to the expected productivity without the fuel loading modification.

Due to the paucity of forest floor bulk density information for southeastern forests, new bulk density conversion factors for the dominant forest types on the SRS were developed to compute litter and duff fuel loading in tons/ac/in.



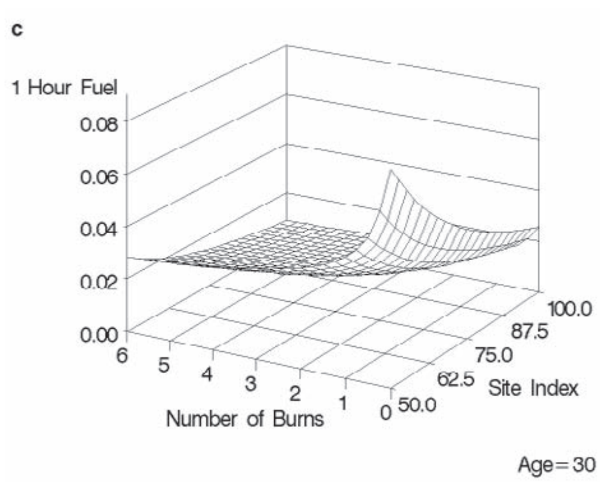


Figure 7—Response surfaces illustrating trends in fuel levels as a function of stand variables and burning history: a) ladder fuel based on equation 1, b) litter-duff fuel based on equation 2, c) 1 hour fuel based on equation 3, d) 10 hour fuel based on equation 4, and e) 100+ hour fuel based on equation 5.

These conversion factors should prove useful for similar forest types of the upper coastal plain and piedmont forests of the Southeastern U.S.

The pattern of fuel loading across the forest types, age, stocking and fire frequency reflects land use history, stand dynamics, stand management and fire management. For the major forest types (loblolly, longleaf, slash, pine-hardwood, hardwood-pine, and hardwood) stand variables generally explained the larger fraction of the variability in the fuel components. Age, BA, and SI explained a large proportion of the variability in individual components, but particularly ladder fuels and 100 hour+ fuels. Natural stand dynamics even in these highly disturbed systems dominated the observed relationships. Ladder fuels decreased with age probably as a result of two factors. Small trees and shrubs are predominant in young stands simply as a result of early succession. As the stands age, the mid-story shrub component is suppressed by the overstory. In addition, land use history also plays a role on these sites. The older pine types were generally planted on old-fields established during the 1950's. These stands had most of the hardwood shrub component eliminated through farming. Later plantations were established in cut-over lands with little effected control of the competition. More recent stands were established on an array of sites with a wide range in ladder fuel species development.

In contrast, stand management probably has a major influence on the relationship between BA and ladder fuels for the managed pine types. The lower BA stands have reduced ladder fuels and mid-story components as a result of disturbance from mechanical harvesting through repeated thinning operations, coupled with prescribed fire. The only fire variable affecting ladder fuels was YSB, but the impact was relatively small. Restriction on environmental conductions during prescribed burning, particularly wind, humidity, and fuel stick moisture, probably limits the fire intensity such that only smaller diameter woody trees and shrubs are killed or controlled. Most prescribed fire activities have also historically been applied during the dormant season, in contrast to the growing season. The latter period is recommended for burning when the objective is to control mid-story shrubs and ladder fuels.

The major fuel type controlling surface fire rate of spread in these stands is the litter and duff and the 1 hour fuel components. Numerous studies of prescribed burning fuel consumption at the SRS demonstrated that these components are the largest fraction contributing to fuel consumption following burning (Kilgo and Blake 2005). Using longleaf pine as an example, it is clear that the previous dominant management paradigm that stands should be burned every five to seven years may not be an effective frequency to reduce hazard fuels within stands. Not withstanding the influence of the spatial distribution of fuel treatments on the rate of spread of catastrophic large wildfire, it appears that a two-to three year burning cycle is critical to effectively reduce these fuels (Outcalt and Wade 2004). This study has established a baseline for future fuels management and policies and provides insight into factors contributing to fuel dynamics for upper coastal plain forests.

Acknowledgments

The authors wish to thank Dr. John Blake, Assistant Manager Research, of the Savannah River Site for his peer review of this manuscript. Funding was provided by the Department of Energy-Savannah River Operations Office through the U.S. Forest Service Savannah River under Interagency Agreement DE-AI09-00SR22188.

References

Brown, J. K. 1974. Handbook for inventorying downed woody material. General Technical Report INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Brown, S.; Schroeder, P.; Birdsey, R. 1997. Aboveground biomass distribution of US eastern hardwood forests and the use of large trees as an indicator of forest development. Forest Ecology and Management 96: 37-47.

Hansen, M. H.; Frieswyk, T.; Glover, J. F.; Kelly, J. F. 1992. The Eastwide forest inventory data base: users manual. Gen Tech. Rep. NC-151. St Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 48 p.

Keane, Robert E.; Mincemoyer, Scott A.; Schmidt, Kirsten M.; Long, Donald G.; Garner, Janice L. 2000. Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico, [CD-ROM]. Gen. Tech. Rep. RMRS-GTR-46-CD. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 126 p.

Kilgo, J. C.; Blake, J. I., editors. 2005. Ecology and management of a forested landscape: Fifty years on the Savannah River Site. Covelo, CA: Island Press. 430 p.

Maier, B.; Ottmar, R.; Wright, C. 2004. Forest floor bulk density and depth at Savannah River-draft final report. USDA Forest Service Savannah River, New Ellenton, SC. Available online: www.osti.gov.

McNab, Henry W.; Edwards, Boyd M., Jr.; Hough, Walter A. 1978. Estimating fuel weights in slash pine-palmetto stands. Forest Science 24 (3): 345-358.

Ottmar, Roger D.; Vihnanek, Robert E. 2000. Stereo photo series for quantifying natural fuels. Volume VI: longleaf pine, pocosin, and marshgrass types in the Southeast United States. PMS 831. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 56 p.

Ottmar, Roger D.; Vihnanek, Robert E.; Mathey, Jared W. 2003. Stereo photo series for quantifying natural fuels. Volume VIa: sand hill, sand pine scrub, and hardwoods with white pine types in the Southeast United States with supplemental sites for volume VI. PMS 838. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 78 p.

Outcalt, Kenneth W.; Wade, Dale D. 2004. Fuels management reduces tree mortality from wildfires in Southestern United States. Southern Journal of Applied Forestry 28(1): 28-34.

Parresol, B.R. 2004. Point and fixed plot sampling inventory estimates at the Savannah River Site, South Carolina. USDA Forest Service Savannah River, New Ellenton, SC. Available online: www.osti.gov.

Parresol, B. R. 2005. Report on analysis of forest floor bulk density and depth at the Savannah River Site. USDA Forest Service Savannah River, New Ellenton, SC. Available online: www.osti.gov.

Scholl, E. R.; Waldrop, T. A. 1999. Photos for estimating fuel loadings before and after prescribed burning in the upper coastal plain of the southeast. Gen. Tech. Rep. SRS-26. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.